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THE USE OF SMALL COOLERS IN A MAGNETIC FIELD

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ABSTRACT

Small 4 K coolers are used to cool superconducting magnets. These coolers are usually used with high temperature suerconductor (HTS) leads. In most cases, magnet is shielded with iron or active shield coils. Thus the field at the cooler is low. There are instances when the cooler must be in a magnetic field. Gifford McMahon (GM) coolers or pulse tube coolers are commercially available to cool the magnets. This paper will discuss how the two types of coolers are affected by the stray magnetic field. Strategies for using coolers on magnets that generate stray magnetic fields are discussed

KEYWORDS: 4 K Coolers, Magnetic Field.

INTRODUCTION

The Muon Ionization Cooling Experiment MICE [1] will have seven superconducting magnets, three liquid absorbers and two detector cryostats that will be cooled with 4 K coolers. Depending on the as built heat leaks, the MICE channel will be cooled using from 19 to 23 coolers. Many of these coolers must operate in a magnetic field. As a result, the ability for the 4 K cooler to operate in a magnetic field will be one of the selection criteria for the type of cooler to be used. The MICE channel shown in FIGURE 1 has three types of magnet modules, the tracker magnet module [2], the absorber focus coil (AFC) module [3] and the RF coupling coil (RFCC) module [4]. The tracker module consists of a three-coil spectrometer magnet that produces a uniform field and two match coils. The AFC module has two coils around a liquid absorber. Two of the coolers cool the AFC magnet and a single cooler cools the liquid hydrogen absorber. The RFCC module consists of four 201.25 MHz cavities and a superconducting coupling coil around them.

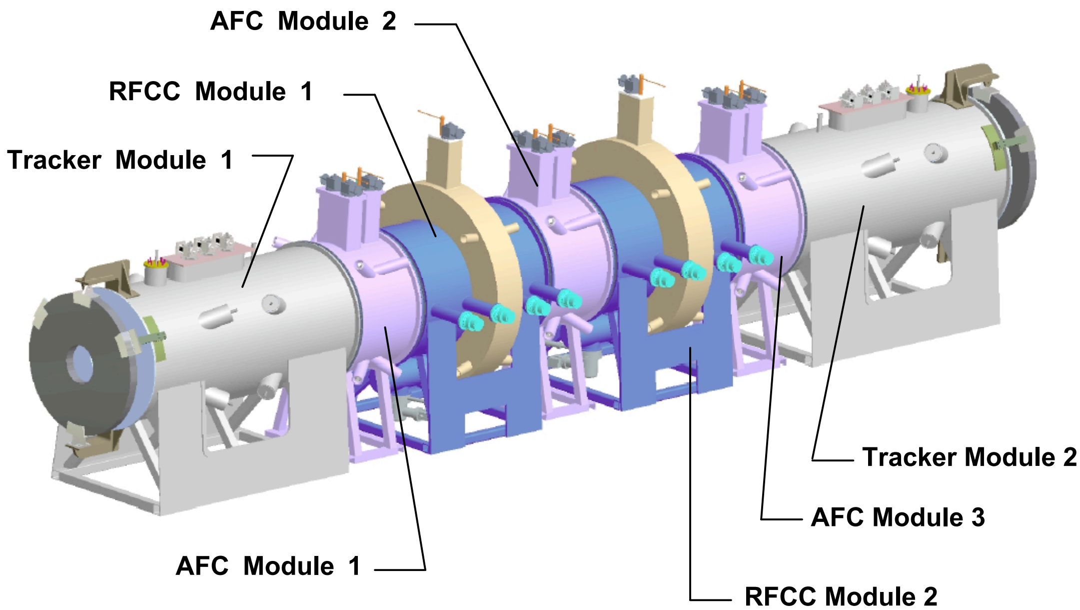


FIGURE 1. The MICE Cooling Channel with the Two Spectrometer Magnets on the Ends of the Channel

FIGURE 1 shows the three types of modules for MICE. There are no shields (either iron or active) for any of the MICE solenoid magnet modules. MICE can operate in a number of magnetic modes. The channel can operate in the full flip mode where the solenoid field polarity changes in each AFC magnet or it can operate in the full non-flip mode where the polarity of the field does not change anywhere in the MICE channel. There are two possible mixed flip and non-flip modes possible as well.

The tracker modules produce a uniform field (to better than 0.3 percent) over a volume that is 1 meter long and 0.3 meters in diameter within the 2.5-meter length of the tracker solenoid. The good field region is generated by a three-coil spectrometer solenoid set that is powered on a single set of the 300 A leads. The two coils that match the field in the rest of MICE with the spectrometer magnet are also powered by 300 A power supplies. All of the coils in the tracker module run at the same polarity. As a result, the magnetic induction on the outside of the cryostat where the coolers are located is less than 0.05 T. The coolers that cool the detectors for the tracker are located over 1.2 meters from the tracker magnet axis. The magnetic induction at the four detector 4 K coolers is less than 0.03 T (300 gauss). The detector coolers are not in vertical orientation, whereas the magnet coolers are vertical with the cold end down (with respect to gravity).

The focusing magnet consists of two coils. Each is separately powered so that the magnet can be operated in the flip mode (with the two coils at the opposite polarity) or the non-flip mode (the solenoid mode where both coils operate in the same polarity). The magnetic induction at the three coolers (two coolers that operate at 4 K and one cooler that operates at 20 K) depends very strongly on the operating mode of the AFC module. When the AFC module operates in the flip mode, there is a strong radial field (up to 0.35 T) where the coolers are located. When the AFC module operates in the non-flip mode, the magnetic field is axial and greatly reduced in magnitude (0.05 to 0.06 T).

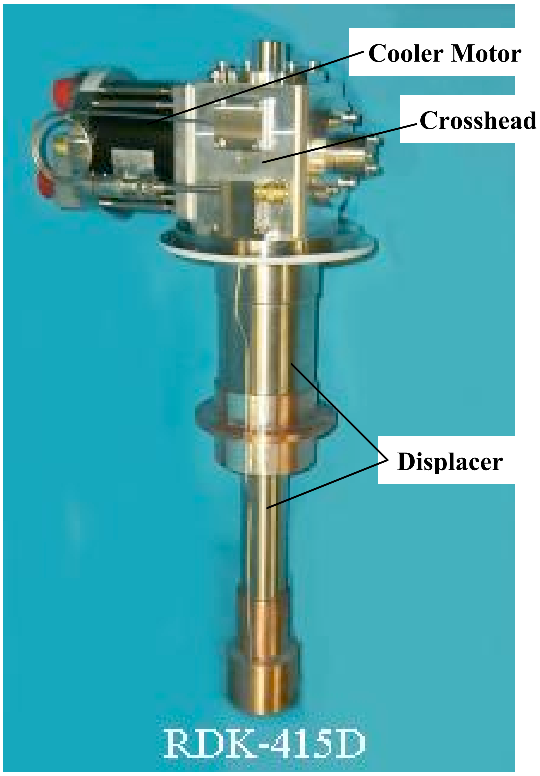
The coupling coil is a single coil that is 285 mm long and 102.5 mm thick. This coil carries is over 3 MA turns. While the field on axis is only a little over 2 T, the field at the coils will be as high as 7.44 T on the inside of the coil and 4.4 T on the outside of the coil. The magnetic induction at the second stage of the cooler is greater than 0.3 T. The field at the cooler top plate can be as high at 0.24 T. The cooler magnetic field is predominately in a direction that is parallel to the solenoid axis.

GM COOLERS VERSUS PULSE TUBE COOLERS

There are two types of commercially available 4-K coolers. These coolers either use the GM cycle, or they use a pulse tube cycle that is similar to the GM cycle. Both types of coolers will produce up to 80 W of cooling on the first stage (at temperatures up to 80 K) and up to 1.5 W at 4.2 K on the second stage. The performance at 4 K for either type of cooler is dependent on the heat load on the first stage. When a 4 K cooler is used to cool a superconducting magnet, the heat load from the electrical leads is taken up by the cooler first stage along with radiation heat leaks through the MLI, conduction heat loads down the cold mass supports, neck tubes, and instrumentation wires. In general the heat load down the current leads is the dominant first stage heat load. The second stage heat load is split between heat leaks down the cold mass supports, heat leaks through the MLI, and conduction heat loads down the leads. All of the heat loads into the cooler second stage are influenced by the cooler first stage temperature. Each type of cooler has its advantages and disadvantages in terms of cooling superconducting magnets.

1.5 W GM coolers, such as the Sumitomo RDK-415D cooler, produce 60 W of cooling at 55 K on the first stage at a line frequency of 60 Hz. At 50 Hz, the cooler first stage temperature increases to about 70 K. The first stage performance is adequate for magnet operation at either frequency. A distinct advantage of a GM cooler is that it can be operated over a wide range of angular orientation. Cooler performance varies ~15 percent even when the cooler is operated in the horizontal orientation. This is why GM coolers have been used on antennas, telescopes, vacuum pumps and other pieces of equipment that must be able to change orientation. In general, 4-K GM coolers require less electric power to operate. For some applications, vibration from a GM cooler can be troublesome. Regular maintenance of the cold head assembly is required. The regular maintenance requires that the cooler be removed from the magnet. This can require that the magnet be warmed up. When the proper maintenance is done, GM coolers are very reliable. An RDK-415D GM cooler cold head is shown on the left side of FIGURE 2.

1.5-W pulse tube coolers, like the Cryomech PT415 cooler produces ~60 W at 50 K on the first stage. The operating characteristics of the PT415 cooler are not dependent on line frequency provided the cooler is charged with helium gas correctly. Pulse tube coolers are well suited for applications where vibration is a factor. (With most superconducting magnets, cooler vibration is not a factor.) Pulse tube coolers require almost no maintenance of the cold head. Pulse tube coolers are well suited for a drop in configuration. The rotary valve and ballast assembly can be moved up to 1 meter away, with a ten percent change in cooler output from the cooler cold head assembly. There are pulse tube cooler users that have run their cooler cold heads for more than 50000 hours without maintenance. Pulse tube cooler performance does not seem to degrade with time, unless the cooler is charged with dirty gas. Pulse tube coolers make excellent helium liquefiers, if the system is set up for helium liquefaction. A refrigeration to liquefaction coefficient as low as 40 J seems to be possible with a well-designed helium liquefaction system employing a pulse tube cooler [5]. A distinct disadvantage of a pulse tube cooler is that it must be operated in the vertical orientation with the cold end down (with respect to gravity). A change in the operating orientation of 15 degrees can degrade the cooler performance by 15 or 20 percent. Commercial, pulse tube coolers available today will not produce cooling when horizontal. The pulse tube coolers that are currently available require more electric power to operate. There have been improvements in efficiency in recent years, so this may change. The discount in the price of a 4-K pulse tube cooler is lower than the discount for a GM cooler, because there are more GM coolers being made. A PT415 cooler cold head is shown on the right side of FIGURE 2.



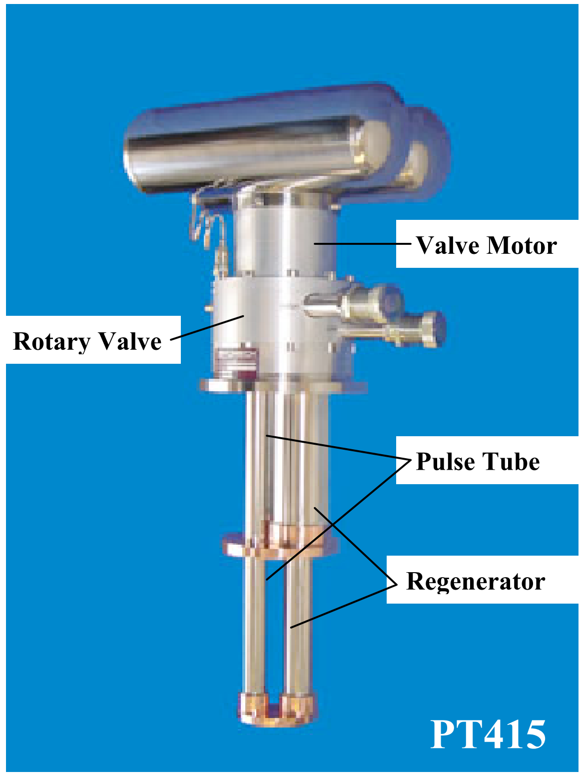


FIGURE 2. Commercially available coolers that produce 1.5 W of cooling at 4.2 K. The RDK-415D GM cooler is on the left side of the figure. The PT415 pulse tube cooler is on the right side of the figure.

SMALL COOLERS IN A MAGNETIC FIELD

Depending on the as built heat leaks in the magnets, the MICE channel will be cooled using anywhere from 19 to 23 coolers. Since the MICE channel has no iron shielding, all of the MICE channel magnets will have their coolers in a magnetic field to some degree. As a result, the ability for the 4-K cooler to operate in a magnetic field will be one of the selection criteria for the type of cooler to be used on the MICE magnet modules. This section will address the effect of the magnetic field on the cooler compressor module, and the cold heads. The discussion includes the cold heads for both types of coolers.

The Effect of Magnetic Field on the Cooler Compressors

The cooler compressors must not be in a magnetic field that is greater than 0.02 T (200 G). The compressor motor has a large quantity of iron within it. The compressor casing may also be made of magnetic steel. The iron and compressor case will be produce large forces between it and the nearest magnet. There is enough iron in the motor magnets to cause the field within a magnetic channel, such as the MICE channel, to be distorted.

The length of the metallic hose between the cooler cold heads and the compressor is usually 20 meters for both types of coolers. In most cases this is enough distance to ensure that the compressor is not in a magnetic field greater than 0.02 T. Cooler compressors can be more than 20 meters from the cold head, but the cold head cooling is often degraded because of the added distance between the cold head and the compressor. Some of the coolers will allow for a length of 100 meters between the compressors and the cold head.

The Effect of Magnetic Field on a GM Cooler Cold Head

The left side of FIGURE 2 shows the cold head of an RDK-415D cooler. There are four components in the cold head assembly that are sensitive to magnetic field. These components are: 1) the cooler crosshead motor that drives the displacers, 2) the crosshead that produces the reciprocal motion of the displacers (the crank assembly), 3) the displacers themselves, and 4) the regenerator material in the second-stage of the cooler. In a three-stage cooler, the regenerator material that counts would be in the lowest temperature stage.

The motor that drives the crosshead is sensitive to magnetic inductions from 0.06 T (600 G) to 0.08 T (800 G) [6]. How much more magnetic induction the motor can take without stalling is not clear. The author has received different answers from different sources. It is not clear if any of the cooler manufacturers have done a proper motor stall test under the full gas pressure loading conditions present in a cooler while it is operating. At some point, the properties of the permanent magnetic materials in the motor will be changed by the magnetic field. The motors for GM coolers used for cryogenic vacuum pumps will operate in a field of 0.08 T, but it is not clear how much more field the motor will take without stalling.

The crosshead that turns the rotary motion of the motor (at 60 to 72 RPM) to a reciprocal motion in the displacers will at some point be affected by the magnetic field. It is quite probable that the magnetic field that affects the crosshead is higher than the magnetic field that affects the drive motor and the displacers themselves.

The displacers will operate in a magnetic field for a while. The limit for magnetic induction on a GM cooler displacer is from 0.05 T (500 G) to 0.1 T (1000 G) [6]. The limits prescribed for the RDK415D depend on to whom one talks. Magnetic field in a direction that is perpendicular to the direction of motion puts a force on the displacer that is both perpendicular to the direction of motion and the magnetic field lines. The force on the displacer causes the displacer piston to rub against the displacer tube walls. This increases the wear on both the piston and the tube wall. The GM coolers used for cryogenic vacuum pumps will run fine with a field on the displacer of 0.02 T (200 G). The cryogenic vacuum pump cooler will work fine at 0.08 T (800 G), but the interval between the cold head maintenance will be reduced over a factor of two. Since the cooler must be removed for maintenance, a reduction of the maintenance interval is an expense, and it adds to the down time when the cooler is not available to keep the experiment cold. Wear on the displacers are the most common cause of GM cooler failure. Field in the direction of motion does not cause added wear on the displacers themselves, but it can cause wear in the crosshead. Even when the field is parallel to the direction of motion of the displacer, the upper limit for the field is probably about 0.15 T (1500 G). Good arguments can be made for keeping the field at the displacer below 0.05 T.

The regenerator material specific heat is reduced in a magnetic field. As a result, the cooler performance at 4 K will be reduced by about ten percent when the field in the second stage regenerator material is above 1.5 T. This is not a problem in GM coolers.

The Effect of Magnetic Field on a Pulse Tube Cooler Cold Head

The right side of FIGURE 2 shows the cold head for a PT415 cooler. There are two components in the cold head that are sensitive to magnetic field. These are: 1) the motor that drives the rotary valve, and 2) the regenerator material in the second-stage of the cooler. In a three-stage cooler the regenerator material that counts would be in the lowest temperature stage. The rotary valve itself is unaffected by the magnetic field and the pulse tube itself is unaffected by magnetic field.

The rotational speed of the rotary valve in a pulse tube cooler determines the frequency of the pulse tube. The rotary valve motor for the PT415 pulse tube coolers is driven by a stepping motor that rotates the valve at 72 RPM. Thus the pulse tube frequency is 1.2 Hz. Since a DC stepping motor is doing the driving, the pulse tube frequency is independent of the line frequency. Thus, the PT415 will produce the same amount of cooling on both stages on 50 Hz power as on 60 Hz power. The charging pressure for the PT415 cooler compressor system is different for 50 Hz power than it is for 60 Hz power. The stepping motor that drives the rotary valve is sensitive to magnetic field. It is believed that this motor can be operated in a field of 0.08 T (800 G) without stalling. The manufacturer recommends that the field at the motor be kept below 0.05 T (500 G). In a PT415 cooler, there are two ways of reducing the magnetic field at the rotary valve motor. These are: 1) move the valve and the displacement tanks on top of the valve to a low field location up to 1 meter from the rest of the cold head. 2) Shield the valve and its motor with an iron shield. Moving the valve away from the cold head will reduce the cooler performance on both stages by 10 percent. If cooler performance on either stage is really important, it is better to shield the rotary valve and its motor. The same arguments can be applied to the rotary valve assemblies for the commercial pulse tube coolers that produce less than 1.5 W of cooling.

As with the GM cooler, regenerator material in a pulse tube cooler will have a lower specific heat in a magnetic field. As a result, the cooler performance at 4 K will be reduced about ten percent when the field in the second stage regenerator material is above 1.5 T.

SHIELDING CRITICAL COOLER PARTS FROM THE MAGNETIC FIELD

We studied magnetic shielding of the critical elements in both the GM cooler cold head and the pulse tube cooler cold head. In order for the magnetic shielding to be effective for either cooler to be used for the MICE magnets, we had to demonstrate that we could shield the cold head critical elements in an external magnetic induction of 0.35 T. The shielding calculations were done in external fields of 0.1 T and 0.35 T with the external fields in parallel to the cold head (in the direction of the displacers in the GM cooler and in the direction of the pulse tubes and regenerators in a pulse tube cooler) and the two directions perpendicular to the cold head direction.

GM Cooler Cold Head Magnetic Shielding

Iron shielding the displacers in a GM cooler is difficult. The displacers vary in temperature between cooler stages. Iron is a good conductor of heat, so a shield around the cooler displacers cannot connect the room temperature part of the cooler with the first stage or the first stage to the second stage. Since the first stage displacer and MLI around the displacer is about 60 mm in diameter, the displacer shield must be at least 20 mm thick.

Shielding the GM cooler crosshead and motor was modeled at Oxford University using TOSCA. The shielding that surrounded the motor was 20 mm thick except the part of the shield around the cooler cold head top plate and the place where the displacer tube sticks down between the cooler top plate and the first stage. When the calculations were done with an external induction of 0.1 T with magnetic fields in various directions, one found that the motor was protected for the field going along the axis of the motor, going along the axis of the displacer and the field perpendicular to the motor axis and the displacer axis. When the external field was raised to 0.35, the shielding to the motor was not adequate in any direction. From the calculations it appeared that the motor couldn’t be shielded with fields in any direction, if the magnetic induction magnitude was 0.2 T or more. It appears that shielding the cold head is not a real option for magnetic inductions above 0.1 to 0.15 T.

Pulse Tube Cooler Motor Shielding

The only part of a pulse tube cooler that needs to be shielded is the motor for the rotary valve that creates the pulses for the pulse tube. A model was made for TOSCA for the 3 D magnetic field calculations and OPERA2D and COMSOL 2D for the axial-symmetric field calculations. The model for the PT415 cooler motor iron shield is shown in FIGURE 3. The axis of rotation for the motor is shown as a dashed line. The magnetic field that is shielded is parallel and perpendicular to the motor axis.

If the aluminum case around the motor and the valve is replaced by an iron case, (see FIGURE 3 when t = 8.2 mm) the valve motor is shielded to 0.04 T when 0.35 T induction is perpendicular to the axis of rotation of the valve. When the induction is parallel to the axis of rotation of the motor, the magnetic induction in the motor is between 0.07 and 0.15 T. If one increases the shield thickness to 33 mm, the maximum induction in the motor is 0.08 T. This suggests that the motor will be well shielded by a 33 mm thick shield at external magnetic inductions of 0.31 T in any direction. There was good agreement between the field calculations done with OPERA 2D and COMSOL 2D, when the external field is parallel to the rotational axis of the PT415 cooler valve motor.

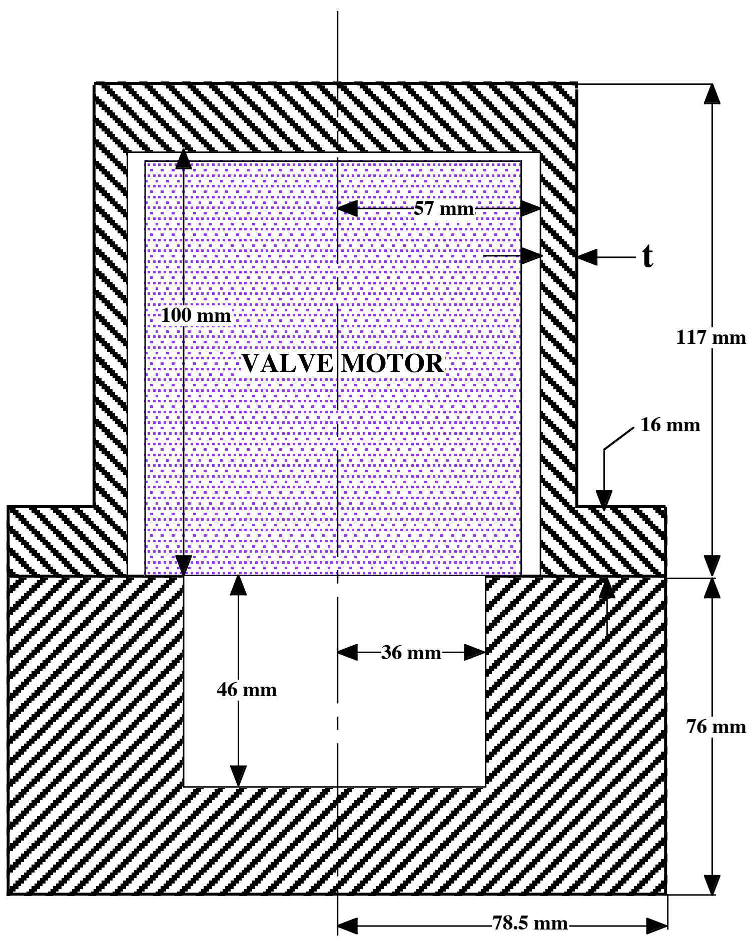


FIGURE 3. The Magnetic Model for the PT415 Cooler Valve Motor Shield (The shield replaces the aluminum case around the motor (t = 8.2 mm) or the shield around the motor itself is 33 mm thick.)

CONCLUDING COMMENTS

The compressor for either the GM or pulse tube coolers must be installed where the magnetic induction is always less than 0.02 T. GM coolers are suitable for many applications where a magnetic field is not present. If the cooler cold head must be operated in any position besides vertical, one must use a GM cooler.

In a GM cooler, the displacer motor and the displacers themselves are sensitive to external magnetic fields >0.05 T. Magnetic fields that are perpendicular to the motion of the GM cooler displacers will reduce the interval between cold head maintenances. The cooler crosshead may be sensitive to magnetic field, but the level of that field is probably higher than the field when the motor stalls.

The only part of a pulse tube cooler that is sensitive to external magnetic fields is the motor that drives the rotary valve. One can operate a pulse tube cooler cold head in a magnetic induction of 0.3 T provided one shields the motor with iron. The amount of iron shielding needed depends on the external field direction with respect to the valve assembly. An alternative mode of operation is to move the rotary valve assembly (with its motor) and the surge tanks into a region where the external magnetic induction is below 0.05 T.

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